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COMPOSITE AIRCRAFT JOINT EXPERIMENTAL TESTING WITH DIGITAL IMAGE CORRELATION

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Abstract: The main goal was to establish results of the individual joint strength characteristics used in composite laminate structure, in order to be used for design computations in airframe structures. A carbon-epoxy composite specimen includes a brass sleeve that is used to connect other metal parts by a bolt, used on light-weight category aircrafts. 11 specimens were tested and pulled by a tensile test machine. The tension mechanisms associated with failure modes of bolted joints in advanced composites is explained. The work is based on experimental test observations, performed by Instron 8516 servo-hydraulic testing machine and analyzed further by Digital Image Correlation (DIC) technique to define failure load of this metal-composite interconnection. Comparison of DIC results is made in parallel with test recorded data as verification. Conclusions include a failure analysis and observations learned during the experiment.

1 INTRODUCTION

1.1 Composite usage in aviation industry

In novel aircraft design there is a huge tendency to use composite materials due to their high tensile strength characteristics and low weight. Numerous examples from aviation industry could be cited to serve as a proof for it and the most well-known is the example of the Boeing 787 commercial airliner. It has more than half of its primary structure made of composite laminates. However, the airplanes cannot be made of the same unit of material, therefore there is always a crucial problem, the primary fittings and connection design. These primary fastener connections can weight a lot over their unit volume. Therefore, the economy of these structural fittings is of high importance. Fittings in control surfaces, design members in wings and in empennage has to have high load carrying capacities, as well as have minimum number of components to allow a more economic design in weight saving.

Considering general aviation, one example of such category to mention is a Polish made jet, Flaris LAR-1. LAR-1 is a five-seated, high performance jet, using composite materials for its components, such as fuselage, wings and empennage. Most of its connections and joints are connected with composite fasteners [1]. The main motive of this work came from a particular composite joint implemented on LAR-1, used to connect metal to composite with an integrated sleeve. LAR-1 with its maximum take-off weigh being 1700 kg, belongs to the European Aviation Safety Agency (EASA) CS-23 Certification Specifications category. The strength properties of the joint are unknown and are essential for design and certification.

1.2 Objective

The desired goal of this research is to find the strength characteristics of such particular, KVT-composite joint and to decide whether such design is fulfilling the design requirement, as stated in CS-23. On Flaris, minor fittings and connections of control surfaces are connected with the help of KVT sleeves. The list of such applications include: elevator and rudder hinge consoles. Apart from Lar-1, other Polish aircrafts such as AF-129, Opal-1 and Samonit utilize KVT sleeves to connect metal parts to composites. From the design point of view, the need for the strength of such a joint is crucial for the certification purposes.

The joint was tested for different cycles in order to have hysteresis and for better statistical data. Direct results of displacements and tensile load can be measured and recorded and then used for finding limit and ultimate tensile loads of such joint.

The secondary purpose of the work is to introduce the DIC method for strength evaluation, analyse and investigate the failure types for such complex joints.

1.3 Experimental test

The experimental testing is performed by *Instron 8516* servo-hydraulic testing machine and analysed further by Digital Image Correlation (DIC) technique, using *GOM Correlate* software. Figure 1. shows a flowchart of the work distribution with different methods.

Digital Image Correlation (DIC) - is an optical method to measure 2D or 3D coordinates for evaluation of displacement and strains. The whole principle is based on stochastic patterns which are applied on the measuring object. The pattern is usually created with black paint, sprayed on a white painted background and using the recorded video of the experimental strength test, the software can calculate 2D or 3D coordinates on the patterns in each individual image. The images at each frame are called: Stages. The deformed pattern represents the deformed object. Depending on the pattern quality, one has to decide about acceptance of the recorded results. If the quality is satisfactory, the case can be analysed, figures of displacements and strains can be prepared [2]. The method is used as an evaluation for industries, especially the ones dealing with motion and advanced materials. Many aerospace disciplines, such as: structural and fatigue testing, vibrations, impact testing and aerodynamics benefit from the analytical investigation.

For the DIC, *GOM Correlate* is used, a free evaluation software for 2D or 3D image/video correlation (in plane testing). GOM allows to measure strain, in both elastic and plastic range. An advantage of the strain measurement method is the contactless determination, by using camera and software. There is no need for any attachment on the specimen like in case of strain gauges. [3]

The measurands in this study are displacements and strains only. In the analysis we are measuring the capacity of the joint rather than the strength of the connection itself.

Figure 1. shows the possible way of verification by comparison of DIC results with test recorded data. Comparative methods include the use of analytical calculation results and/or FEM results. This is however, part of a future work.

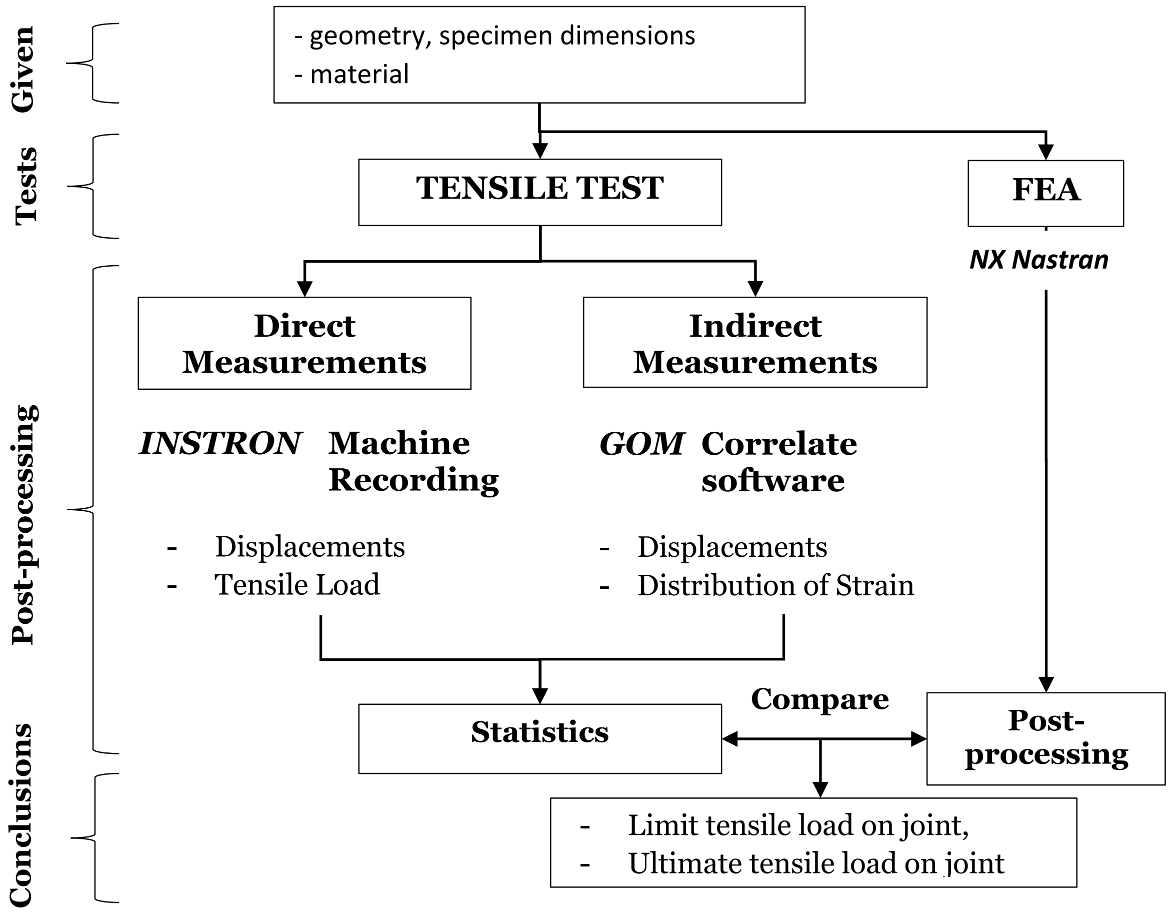

Figure 1. Flow chart of experimental test and analysis

2 COMPOSITE SPECIEMEN

The composite samples are made from 10 layers of Sigratex® SGL KDK 8042 [4] type of 2x2 twin weave (2D) carbon fabric and 3 layers of Interglas 92110 [5] type of 2x2 twin weave glass filament fabric. The layers are oriented in a manner, shown in Table 1. The selection of the 2x2 twin weave pattern is based on its better fabric stability over other types of patterns, such as plain one.

Having the specified fibre direction according to Table 1., one will get a quasi-isotropic lay-up laminate. The dry reinforcement carbon weaves are wet layered manually and adhered with EPIDIAN-53 matrix. After the wet layup process, the composites were adhered and heat threated (60°C for 8 hours). The samples were then drilled and the sleeves (KVT TAPPEX® 0006M5 - MICROBARB®) [6] were adhered with minimal amount of 3M™ Scotch-Weld™ Epoxy Adhesive DP490 and then press fitted. Painting in a form of white dispersed paint on the surface was essential for the DIC method, which is shown on Figure 2.

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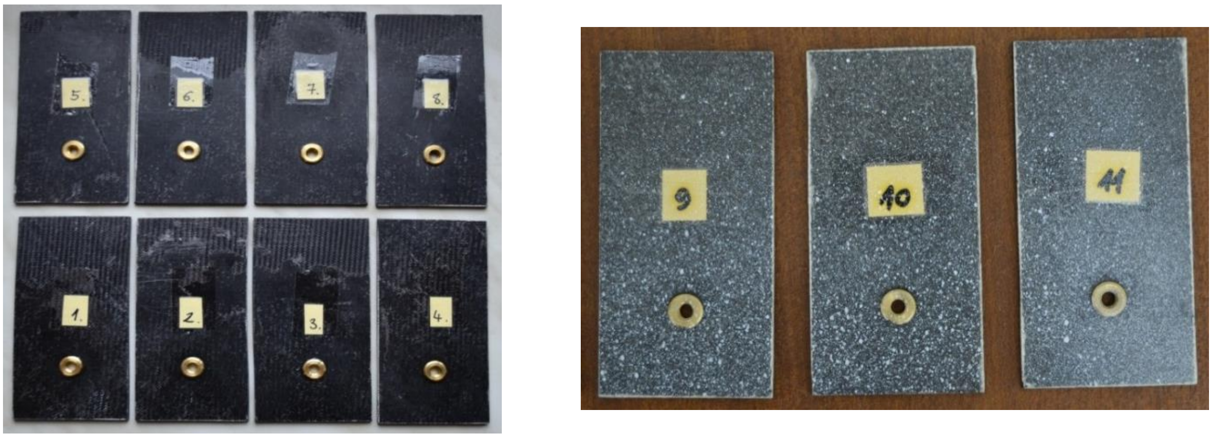

Figure 2. Specimens before (left) and after (right) painting

Layer no.	Material	Thickness (dry) [mm]	Fibre direction
1.	SGL KDK 8042	0,30	0/90
2.	SGL KDK 8042	0,30	-45/45
3.	SGL KDK 8042	0,30	0/90
4.	SGL KDK 8042	0,30	-45/45
5.	SGL KDK 8042	0,30	0/90
6.	SGL KDK 8042	0,30	0/90
7.	SGL KDK 8042	0,30	-45/45
8.	SGL KDK 8042	0,30	0/90
9.	SGL KDK 8042	0,30	-45/45
10.	SGL KDK 8042	0,30	0/90
11.	Interglas 92110	0,18	-45/45
12.	Interglas 92110	0,18	0/90
13.	Interglas 92110	0,18	-45/45
	Total (dry):	3,54	

Table 1. Ply table

3 STATIC TESTING OF SPECIMENS

On Figure 3. the experimental setup is shown that was used for the DIC method.

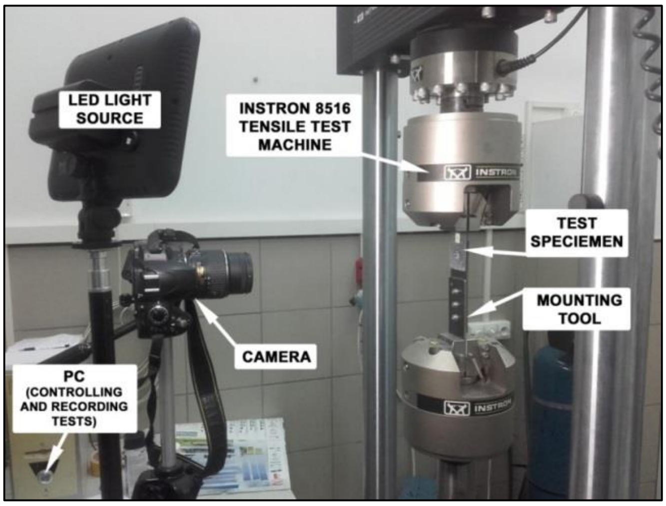

Figure 3. Experimental setup

The test specimens were aligned with a steel mounting tool and connected together by GOST 3024 A-5 12 aviation type bolt (M5x0,25 l=12 mm, eq. to BN-76/1111-05).[7] The tensile test was performed with load controlled setting, for which the desired loading was set to: 6,5 kN, 8,0 kN and finally 9,5 kN with 4 cycles for each specimen. The duration for each cycle is 10 sec tensioned and 10 sec releasing back to 1,0 kN. In order to record failure, the 4^{th} cycle of the 9,5 kN loading was increased to 12 kN, a load higher than the bolt's ultimate strength in shear.

The load level corresponds to a general safety factor of 1,5 as required in CS 23.303. The design load level was proposed after analysing the CFD and the analytical results of Flaris. From the CFD and analytical strength calculations of the components where KVT sleeves are used, one can decide if the strength of the joint is acceptable.

Plot of estimated stress distribution in tension, along with the applied load was made for each element in the joint (bolt, composite, insert). The first load controlled value in the experiment was based on the highest estimated loading. Prior to the tension test, three other specimens were tested and confirmed the final loading values.

4 RESULTS AND CONCLUSIONS

4.1 General

The idea of the DIC is to place the video image in the software that is capable of tracking the randomly dispersed pixels in the selected area and based on the motion of these pixels, calculate the desired values. In this work, the DIC was performed for cases of loading 9,5 kN only.

In each analysed case, the specimen's pattern quality had to be analysed to verify if the DIC method can be applied. After the pattern is checked, scaling must be set, which specify how much the real distance between two selected points is. In this way the video image is computed according to the real dimensions.

4.2 Analysis of recorded results

The following load-deformation hysteresis loop (Figure 4.) of applied load as a function of displacement shows that initially the load increases linearly with the applied load. In case of 6,5 kN loading, there is not a sudden drop as it would be expected for plasticity and it goes back linearly as the load is released (hysteresis). Results plotted for 9,5 kN shows sudden drop at above 8,5 kN, and it lasts until the pull out of the fiber. Similar hysteresis was found for all the other specimens exhibited to the same loadings.

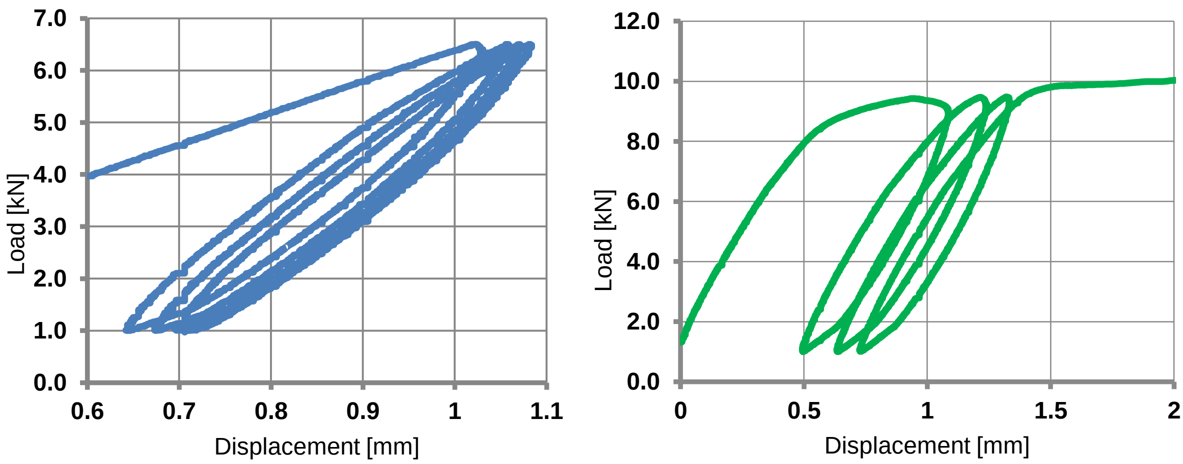

Figure 4. Displacement vs. Load plot of Specimen 2_1 with cyclic loading of 6,5 kN (left) and 9,5 kN (right)

On Figure 5. the cyclic loading is observed as the tension is loaded or unloaded, as a function of time. One can notice that the predefined displacement control has a tendency to grow with each cycle as being tensioned, this indicates how the joint deforms with being loaded multiple times.

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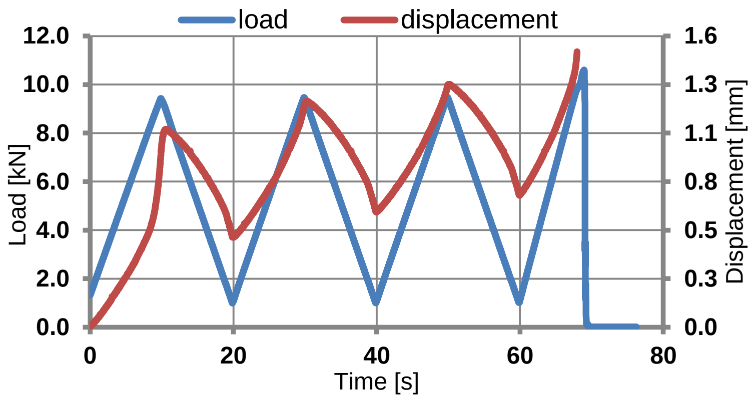


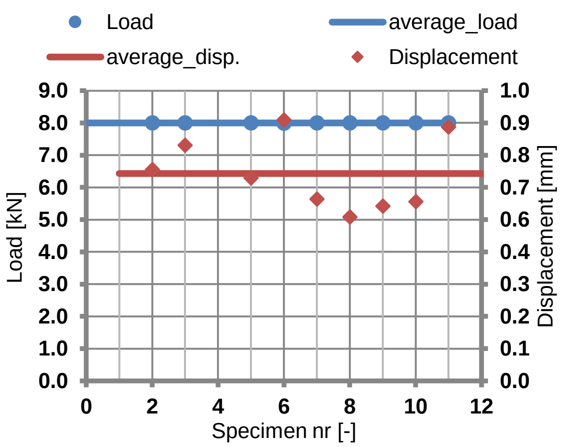
Figure 5. Time vs Load and Displacement plot of Specimen 2_3 with cyclic loading of 9,5 kN

Figure 6. was created to give a quantitative comparison between the specimens, based on collected results of displacement and load corresponding to the highest load peaks at each cycle. One can conclude that all specimens except for #6, has survived the loading of 9,5 kN with cyclic loading at least 3 times. Observation for 8,0 kN shows that nearly half of the batch displaced similarly (0,6-0,9 mm), at this loading small built up or delamination of glass and minor cracks developed on the surfaces. With 9,5 kN, there is a changing distribution in displacement, as well as in loading. Critical and significant failures could be observed at the loadings presented.

Table 2. is intended to give a statistical summary of all the tensioned elements (11 x 3 cycles in total).

		Displacement real [mm]	**Load [kN]**	**Remarks**
Average of all tests		1,1390	7,98	
Average for 6,5kN		**1,3284**	**6,50**	All samples withstood
Average for 8,0kN		**0,7140**	**8,00**	All samples withstood
Average for 9,5kN		**1,3744**	**9,58**	**Critical design limit**
Standard Deviation of Population		**0,9692**	**1,31**	
Significance level	**$F_{95\%}$**	**0,5728**	**0,77**	
	$F_{99\%}$	**0,7527**	**1,01**	
Confidence Interval (CI)		± 0,63	± 0,86	
Standard Error		0,9560	1,3479	

Table 2. Statistical results of displacements and loads



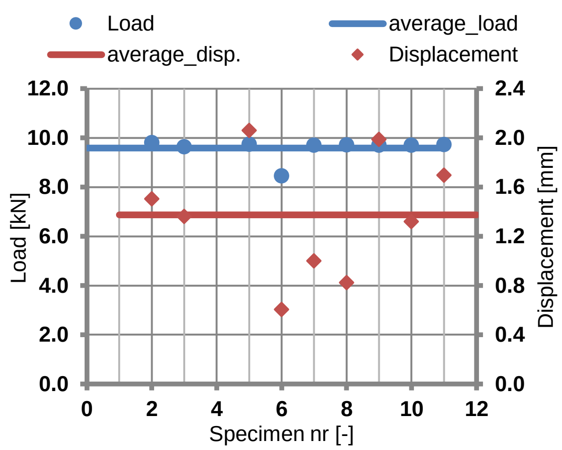


Figure 6. Quantitative comparison of load and displacement for 8,0 kN (left) and 9,8 kN (right)

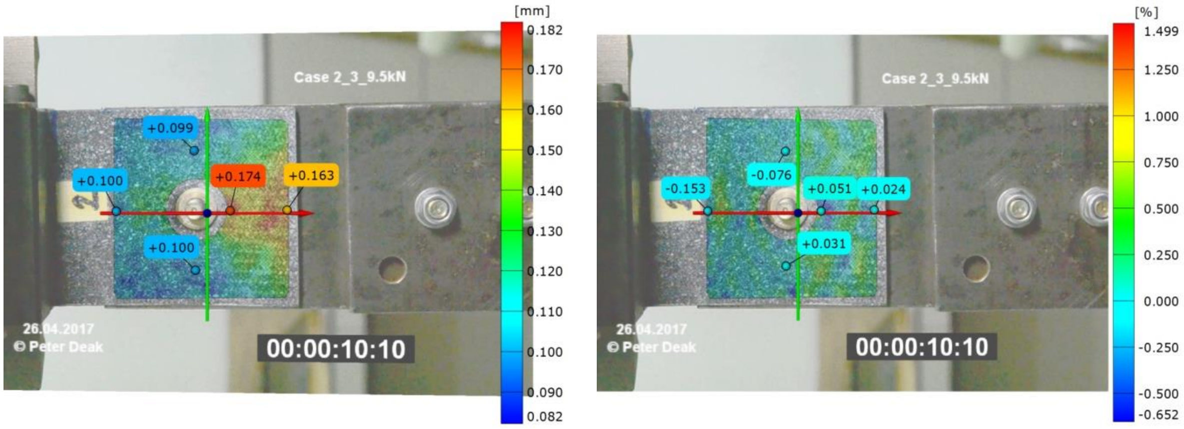


Figure 7. DIC in GOM Correlate software, Displacement distribution [mm] (left) and Strain in X distribution [%] (right) with deviation labels shown

In order to compare the distribution of displacements and strains along the surface, figures of image mapping is made. In this way only the computed area is shown with the colour scale and defined dimensions. The selection of points P1 (leftmost), P2 (bottom), P3 (top), P4 (middle) and P5 (rightmost) was necessary for easier comparison between the other specimens. These are shown with deviation labels on Figures 7 and 8.

GOM software calculates displacements first based on the pattern motion, then taking the partial derivatives in corresponding coordinates will give strains, consequently the influence of displacement is most important, that is why we look for highest displacement values at any Stage and for that Stage getting the plots of eps X and eps Y.

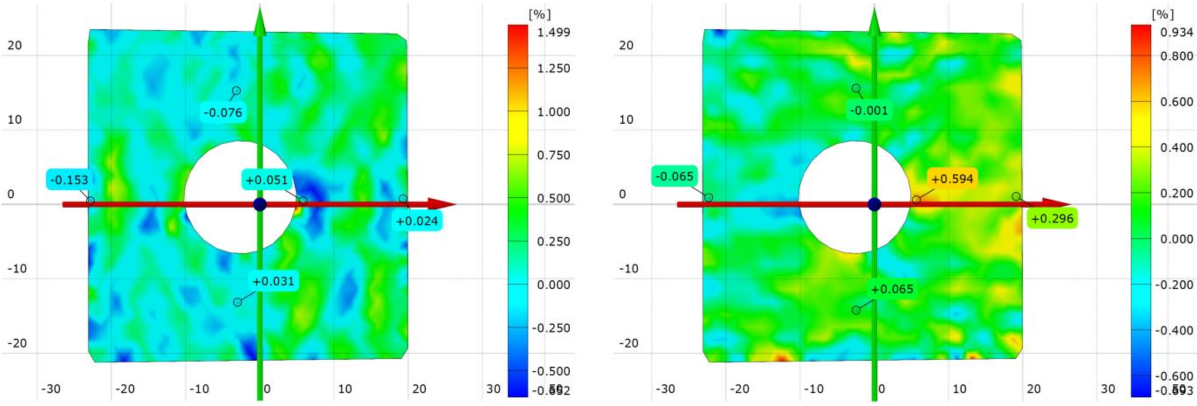


Figure 8. DIC in GOM Correlate software, Strain in X (left) and in Y (right) distribution image mapping

Similarly to displacements, strain in longitudinal and lateral direction (eps X, eps Y) can be turned on and displayed with labels at particular locations, as shown on Figure 8. The colour maps of strains have been generated for 9,5 kN tensile load, for the cases of highest peaks.

4.3 Failure Analysis

This section is dedicated to images from experimental testing, to illustrate the particular failure modes, (bearing, shear-out) damages or observations on the composite joints. By analysing Figure 9. several failure modes can be observed. It can be concluded that failure types in most of the cases was bolt failure, in other cases shear-out of the laminate or simply bolt pulling through the laminate. In most cases (except #1 and #6), the joint is well-working as it was designed, indication bolt failure, that is a satisfying result for the designer. It means that all the specimens with such type of failures would carry the load up to 9,5 kN, for at least 4 cycles. Even though minor cracks, displacements and delamination are seen, the joint would fulfil its function and not detach under such loadings.

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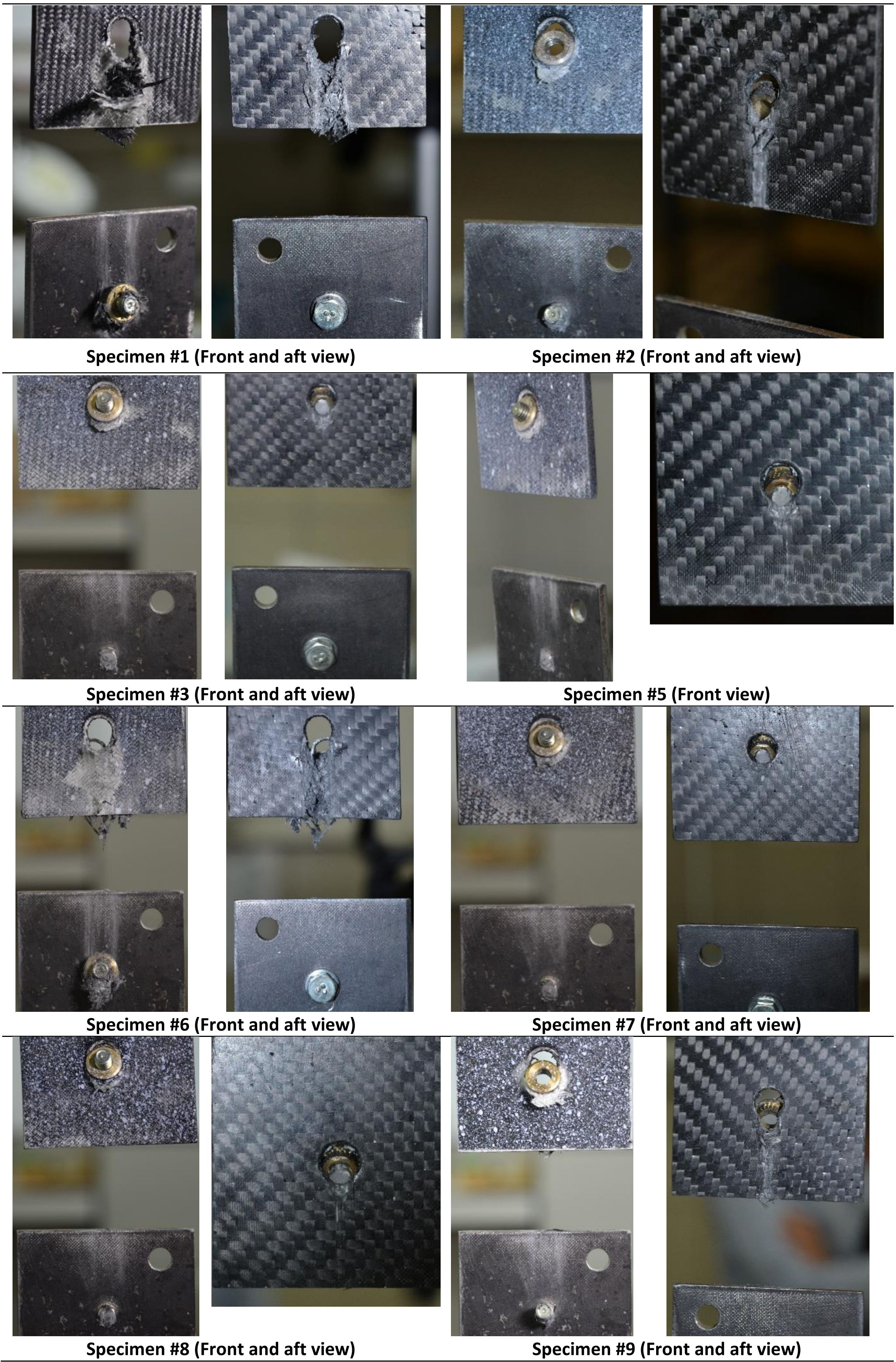

Figure 9. Front and aft views of common failures

4.4 Conclusions

Tests have revealed the main question concerning the wanted order of failure in the proposed assembly. One could conclude that the order of failure in most cases started with delamination or built up of glass fibers on the surface. The consequent noticeable damage affected the brass insert that is most probably due to the failure of the adhesive. It craved the laminate deeper, or in certain case, its thread sheared out. The last failure occurred to the bolt that fractured eventually due to high shear stresses.

The applicability of threaded insert as a connection in composite materials was tested. DIC method was used for determining strain distribution. Fracture mechanics of composite joint structures is still not fully investigated; therefore it is very hard to predict the behavior of such connection.

Observations about graphs of displacements show that as cycles are increased, the maximum displacement is increasing as well. At the 3rd cycle peak, the structure is still considered 'safe', although if the one compares the displacements in the 1st peak with the 3rd one, we can observe that in most of the specimen it has increased by 0,02-0,08 mm. It was concluded that the specimens withstood 3 cyclic loading at a value of 6,5 kN, 8,0kN and 9,5 kN, which defines a critical design limit to 9,5 kN. Further testing with learned observations involved is crucial to give a more confident design value for such a joint.

4.5 Observations and future work

During the experiment and the preparations, many observations were learned that are suggested for a future work in a similar research.

- Clamping torque shall be controlled and set to a given, computed value and the same torque should be applied on the bolt on each specimen.
- Proper alignment of the specimens is crucial, even though it creates still acceptable recording. In case of Specimen #8, the composite was moved out of the axis, but the vector of tension force is still acting at the centre. In addition, it is important to precisely align the force acting line with the theoretical direction, otherwise the misaligned force vector will cause a difference in the composite coupon's strength.
- For the effects of out-of-plane motions, the application of more than one DSLR camera is suggested as according to [8]. Second camera also allows capturing photographs at significant moments. It must be installed on a tripod in order to have the same view on images for easier comparison.

Finite element analysis is essential for validation and justifications of the DIC results. One can use the validated FEM results for future joint designs before testing the specimens, as it is a very expensive and time consuming procedure. With the help of FEM, laminates can be designed better and with higher accuracy. It allows the designer to use the FEM and optimize the specimens, meaning to reduce the cost and weight of composites. Similar research work, using FEM and DIC strain maps with the use of strain gauge involved shows riveted joints in glass fibre reinforced plastics (GFRP) [9].

Additional computation and tests should include other KVT sleeves of different types. KVT offers more sleeves with longer length, with different hole sizes (i.e.: M6, M8) and dimensions.

The research presented in this paper is similar to other work of the co-author [10] conducted on usage of aluminium rivet nuts in composites as mechanical joints. Other works related to current state-of-the art in testing of such interconnections can be found in reference [11-12].

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